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NOTES ON THE MECHANICS OF GEOLOGIC STRUCTURES

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INTRODUCTION

Since an early date in the development of the science of geology it has been recognized that secondary structural features are the results of failure or yielding of rocks under deformative forces, and students of geology have attempted to interpret these secondary features in terms of the forces and movements which produced them. Because of the great size and heterogeneity of the earth masses involved, the analysis of the casual mechanics of a given major structural feature is never a simple matter. The geologist, not having witnessed the production of the structural features at hand, or of any similar features, finds it difficult to view the problem in perspective and in proper relationship to associated structural features.

Discussions of the mechanics of deformation in geologic literature on the whole indicate a rather elementary conception of the factors involved and a tendency to assume more or less arbitrarily a simple set of mechanical conditions, when the structures observed may be susceptible of several alternative explanations. A single structural feature or group of similar features is not necessarily indicative of the type of deformation involved. A group of intersecting faults may be looked upon as a sequence of unrelated events, when, with equal or better reason, they might be considered as essentially simultaneous and due to a single deformation. The two interpretations require a widely differing structural history of the region involved.

An open fissure obviously due to tensional stresses (so far as the fissure itself is concerned) may be an incident in simple elongation, shear, cross-bending, compression or shortening, or torsional warping. A reverse fault implies conditions of shortening or compression but may in addition to this possibly be an incident in a general shearing movement, or a phenomenon of simple cross-bending, or may be due to torsional warping. A series of folds may be due to shortening or compression in a direction normal to the trend of the folds or to a general shearing movement in a direction at a considerable angle to the trend. In general the shearing type of deformation has been largely neglected in analyses of the mechanics of geologic structures, both fractures and folds.

It is in part the purpose of this paper to present the result of experimental work which illustrates the variety of mechanical explanations possible for a given structure, and incidentally to emphasize the extent to which many of these may be related to shearing, which the writer regards as an exceedingly common type of deformation in rock movements. It is further purposed to present and to illustrate experimentally analyses of the stresses involved in the various types of deformation.

DESCRIPTION OF APPARATUS

Several years ago the writer devised for use in the structural geology laboratory of the University of Wisconsin a simple type of apparatus for studying and demonstrating relations of fractures and of folds to the forces producing them. The apparatus is used in three forms as illustrated in Figures 1, 2, and 4. These are similar in construction, consisting of a rigid rectangular frame of gas pipe supporting two clamps between which a heavy sheet of rubber is stretched. One or both clamps may be moved in various ways by means of screws so that tension, compression, torsion, and shear, or combinations of these may be produced in the rubber sheet.

The medium in which fractures are produced is a thin coating of paraffin applied to the upper surface of the tightly stretched rubber sheet and chilled until it is brittle. The paraffin coat is best applied by pouring the melted paraffin very rapidly and freely over the rubber sheet, which has previously been warmed practically to the melting-point of the paraffin. The hot paraffin is allowed to drain from the rubber. A little experience soon enables one to judge of the manipulation necessary to secure the thickness desired. The chilling can be accomplished by allowing cold tap water to flow over the uncoated side of the rubber. If chilled too rapidly or too much, cooling cracks will develop in the paraffin. Deformation of the rubber sheet produces systematic fractures in the paraffin bearing definite relations to the manner of deformation.

Folds are produced by coating the paraffin with a thin layer of plastic wax and laying smoothly over this a very thin sheet of rubber, such as is used by dentists, or a sheet of tinfoil. When the rubber thus coated is deformed, folds are developed in the plastic wax and its coating, as described later.

This type of apparatus has an advantage over the deformation of large masses of material in a compression machine of the piston type, as the forces are transmitted through the rubber and therefore applied at every point in the coating. The thin coat of paraffin may be considered as representing the flat-lying rocks in the zone of fracture, having wide lateral extent as compared with thickness. The sheet of rubber might correspond to the deeper zone of rock flowage. Deformation of the paraffin-coated rubber is comparable to deformation affecting the zone of flow and the overlying zone of fracture simultaneously. A distribution of stresses throughout the deformed mass is obtained. The phenomena of repeated faults or extensive systematic joining and of repeated folds much more closely simulate nature than do the single fractures obtained in a testing machine or the single folds which develop ahead of the piston in the type of apparatus employed by Willis and others.

An apparatus employing a stretched rubber sheet on which plastic layers were built up and deformed by the contraction of the rubber was employed by Alphonse Favre[1] in connection with a study of rock deformation. In order to apply the compressive force he attached wooden blocks to the rubber to serve as buttresses or thrust blocks. The net result was not essentially different from the results obtained by later investigaters employing apparatus of the type used by Willis. A slight modification of the apparatus of Favre was used by Hans Schardt,[1] who used various combinations of plastic and brittle layers in his studies of the mechanics of mountain building. Still another modification of Favre's work was employed by Stanislas Meunier,[2] who studied and described the fractures produced in a layer of partially set plaster on a contracting rubber sheet. These three investigaters confined their work to pure shortening and paid no attention to stresses set up by tension, shear, or warping.

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[1] Alphonse Favre, *Archives des Sciences Physiques et Naturelles,* Nouv. Pér., Tome 62 (Genéve, 1878), pp. 193–211.

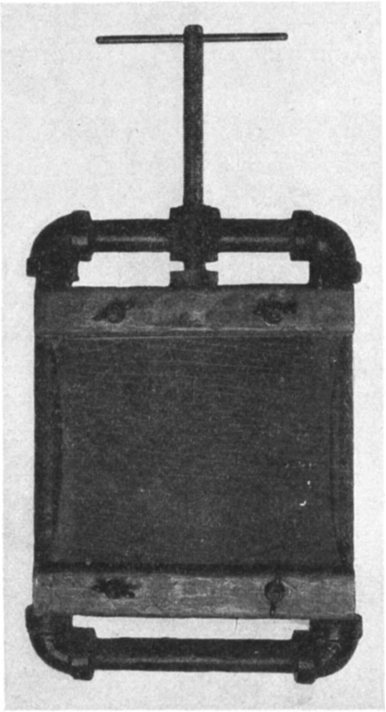

FIG. 1.—Fractures produced by tension. A heavy sheet of rubber is held between two clamps and stretched by means of the screw at the end. It is then coated with paraffin which is allowed to chill until brittle, after which the rubber is further stretched by means of the screw, developing tension cracks in the paraffin.

EXPERIMENTAL RESULTS

Fractures produced by tension.—The apparatus (Fig. 1) consists of a frame with a rigidly attached clamp at one end and a movable clamp at the other which may be moved toward or away from the stationary clamp by means of a long screw. To develop tension fractures the rubber sheet fastened at its edges in the two clamps is tightly stretched by means of the screw and then coated with paraffin which is allowed to chill until brittle. Tension is then applied by further stretching of the rubber by means of the screw. A typical set of tension fractures thus developed is shown in Figure 1.

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[1] Hans Schardt, "Études géologiques sur le Pays-d'Enhaut Vaudois." Troisiéme partie. A. Mécanisme des Dislocations. Chapitres xv–xvii. Planches VI–IX. *Bulletin de la Soc. Vandoise des Sciences naturelles,* Vol. XX, No. 90, 1884.

[2] Stanislas Meunier, *La Géologie Experimentale* (Paris, 1899), p. 299.

These are approximately at right angles to the direction of movement as is to be expected. They are open cracks perpendicular to the rubber sheet. These results are what an analysis of the mechanics involved would indicate. The paraffin, like rock, is less resistant to tensional stresses than to shearing stresses. It fails, therefore, by the development of breaks along planes which are perpendicular to the maximum stress.

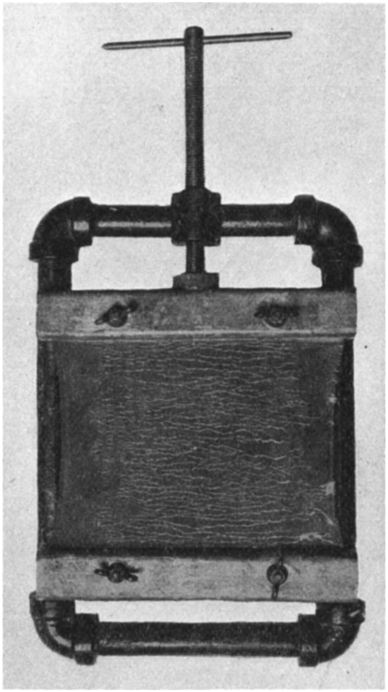

FIG. 2.—Fractures and faults developed by shortening or compression. This is the same apparatus as shown in Figure 1. The heavy sheet of rubber is first tightly stretched by means of the screw, coated with paraffin which is made brittle by chilling, after which the rubber sheet is allowed to contract by means of the screw, thus producing compressional stresses in the paraffin. Figure 3 shows these compression fractures in detail.

Fractures produced by compression.—The apparatus used for this purpose is the same as the one employed for tension. The compressive force is applied by releasing the screw and allowing the rubber to contract. This develops compressional stresses in the paraffin coat. The first breaks to appear are small inclined thrust faults striking at right angles to the direction of shortening and dipping approximately 45° either way. (See Figures 2 and 3.) These are followed by small number of vertical faults which strike at angles approximately 45° to the direction of shortening (seen near the margin of the rubber sheet in Figure 2) and are due to the fact that lateral relief is afforded at these points by the "spread" of the rubber sheet. There also appear a number of vertical tension joints striking in the direction of shortening and apparently due also to the "spread" of the rubber.

An analysis of the mechanics involved leads to conclusions in accordance with the foregoing experimental results. Under simple compression, fracture takes place by breaks which develop in the planes of maximum shear.[1] Therefore the paraffin should fracture along planes inclined at approximately 45° to the direction of the compressive force. The development of these inclined shear fractures requires actual displacement on the plane of fracture. This movement has a component parallel to the compressive force and also one at right angles to this force. Evidently, therefore, fractures can develop only in such an attitude as permits this movement to occur. In the central part of the rubber sheet the direction of easiest relief is upward or away from the surface of the rubber and therefore we expect inclined fracture planes striking at right angles to the direction of compression. Near the margin of the rubber sheet lateral relief is afforded, and we find

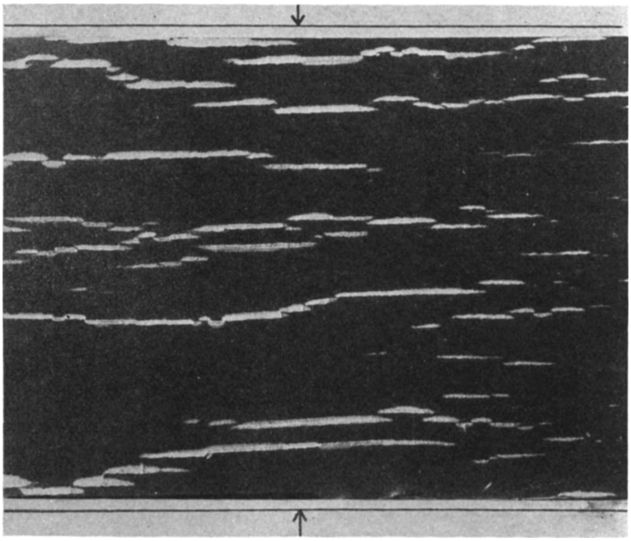

FIG. 3.—Fractures and thrust faults produced by shortening or compression in the direction of the arrows. (See Fig. 2.) The white bands are fractures and thrust faults in the paraffin which strike at right angles to the direction of shortening and dip at angles of approximately 45° in either direction.

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[1] C. K. Leith, *Structural Geology*, p. 16.

vertical fracture planes striking at angles of approximately 45° to the direction of compressive force.

This experiment in terms of earth movements is to be compared with a tangential shortening of an earth mass extending down into the zone of flowage, accompanied by side flowage or spread. This shortening is communicated to the rocks in the zone of fracture, resulting in inclined thrust faults striking normal to the direction of shortening, vertical shear faults striking at angles of approximately 45° to the direction of shortening and vertical tension joints striking in the direction of shortening.

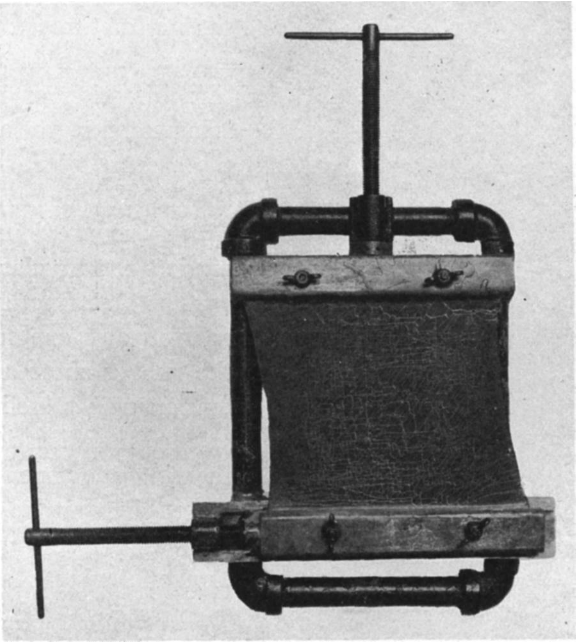

FIG. 4.—Fractures and faults developed by shear or rotational stress. A heavy sheet of rubber is tightly stretched between the two clamps by means of the screw at the top and coated with a thin coat of paraffin which is made brittle by chilling. The paraffin-coated rubber sheet is then deformed by means of the screw at the left. The fractures developed by the shearing movement are shown in detail in Figure 5.

Fractures produced by shear or rotational stress.—The apparatus used for this purpose is shown in Figure 4. It has one clamp which may be moved toward or away from the other by means of a screw. The other clamp is mounted in a slide and by means of the second screw may be moved at right angles to the direction of movement of the first clamp. The sheet of rubber is tightly stretched between the two clamps, coated with paraffin, and deformed by means of the screw attached to the sliding clamp. This subjects the rubber sheet and its coat of paraffin to a shearing or rotational stress. The resulting fractures in the paraffin are shown in Figure 5. The direction of movement is indicated by the arrows and the amount of movement by the shape of the parallelogram which was, previous to deformation, rectangular.

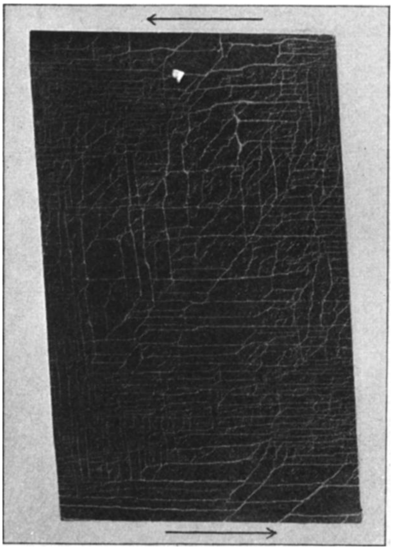

FIG. 5.—Fractures produced in paraffin coat on rubber sheet by shearing. The arrows indicate the direction of movement and the shape of the figure shows the amount of distortion.

The first fractures to appear in any one locality on the rubber sheet are usually tension cracks inclined about 45° to the direction of the shearing movement. These are at right angles to the direction of maximum elongation and appear as vertical open cracks. They are followed immediately by two sets of vertical faults with horizontal displacement, one set striking parallel to the direction of movement and the other parallel to the free edges of the rubber sheet. These represent two directions of non-distortion or two shear planes developed by the shearing movement in which direction of relief is in the plane of the paraffin layer. Another set of faults, only two of which are shown in Figure 5, are thrust faults striking approximately at right angles to the tension crack and inclined approximately 45° dipping in either direction. These are due to compression in a direction at right angles to the direction of maximum elongation.

The pattern of fractures developed in a series of experiments with varying thickness of paraffin coat is uniform in so far that the foregoing described set of fractures are always found. Their relative prominence, however, varies with the thickness and brittleness of the paraffin coat.

Fractures produced by torsional warping.—It is difficult to form any estimate of the importance of this type of deformation, but it seems probable that torsional warping occurs and, therefore, that it merits consideration as one of the types of earth deformation.

A warped surface may be considered as having been deformed in two manners; namely, by the change in area which has engendered tensional or compressional stresses or both and by bending which has occasioned stresses characteristic of cross-bending. For purposes of the present analysis it appears best to consider these two phases of deformation independently.

Changes in area due to warping.—If a sheet of rubber is held between two clamps, as in Figure 6, and subjected to torsion by turning one of the clamps (maintaining a constant distance between the clamps) the effect is to increase the area of the rubber

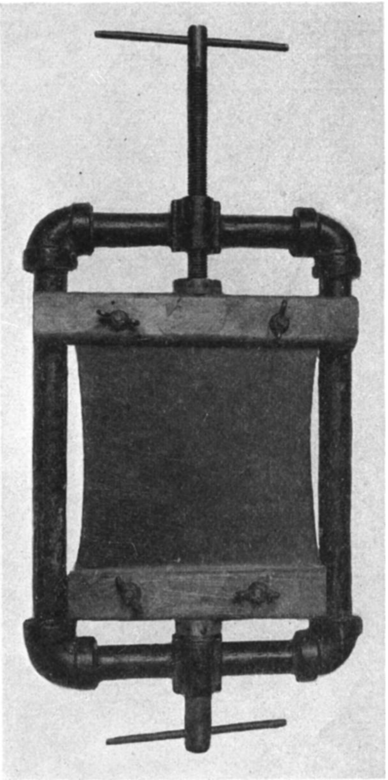

FIG. 6.—Fractures produced by torsional warping. A heavy sheet of rubber is tightly stretched between the two clamps by means of the screw, and coated with paraffin which is made brittle by chilling. Then the lower clamp is rotated by means of the handle at the lower end. This subjects the rubber sheet to torsional deformation and develops cracks in the paraffin. (See Fig. 7.)

sheet. Plainly the center line of the rubber (the axis of torsion) remains unchanged in length, but the lateral margins are stretched, because the rotating of one clamp increases the distance between the ends of the two clamps. This stretching is maximum at the free edges of the rubber and decreases toward the center. The effect of tension thus developed is illustrated in Figure 7, which shows the cracks developed in the paraffin layer as a result of torsional warping of the rubber. Distribution of the cracks shows plainly the increase in the amount of tension as the margin is approached. The confluent nature of the cracks, resulting in a minimum number of free ends, is an interesting feature.

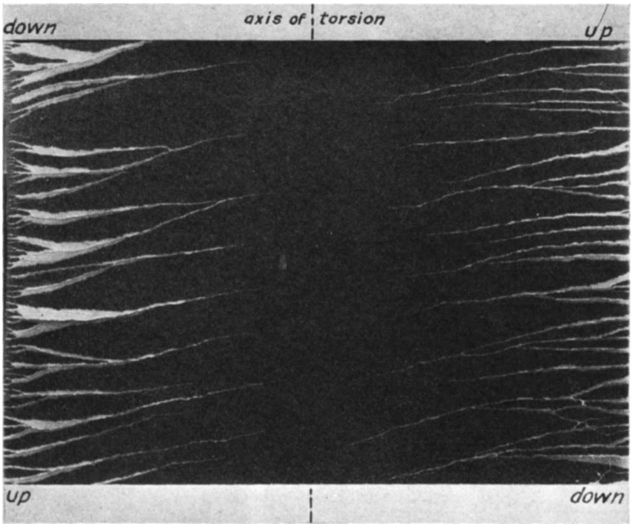

FIG. 7.—Fractures produced in paraffin coat on rubber sheet by torsional warping. (See Fig. 6 and 10C.)

The rubber sheet may be so arranged that the free edges remain constant in length during torsion. If the rubber sheet thus mounted is subjected to torsion, there can be no change in the lateral margins. There is a change, however, along the center line because the turnable clamp approaches the other as it is turned, thus causing shortening or compression along the center line. This compression is maximum along the center line and decreases to zero at the edges. A paraffin coat on the rubber sheet thus deformed develops characteristic overthrust faults of the type shown in Figure 3, which are most numerous along the center line and decrease in abundance and displacement toward the margin.

We have in these two types of deformation limiting cases, neither of which is probably realized under natural conditions. In the first case there is a net increase in area; in the second case a decrease in area. We may now consider an intermediate case in which the total area remains constant. This in terms of the rubber sheet would result in tensional stresses along the free margins and compressional stresses along the center line with a neutral zone of neither compression nor tension on either side of the center. These three cases are illustrated in Figure 8. In each case the rectangular area represents the outline of an undeformed surface. The area with curved ends represents the surface

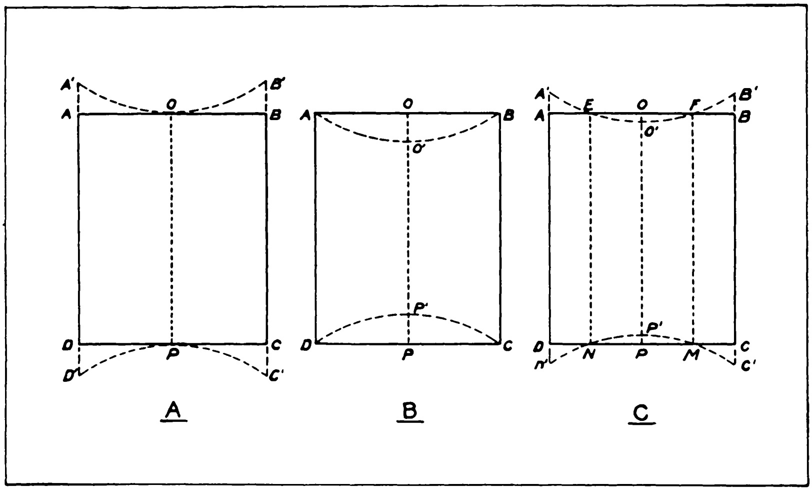

FIG. 8.—Illustrating changes in area due to torsional warping of a rectangular surface. In A the line *O–P* on the axis of torsion has remained constant in length resulting in a net increase in area from *ABCD* to *A'OB'C'PD'*. In B the lateral edges have remained constant in length and the result of warping is a decrease in area from *ABCD* to *AO'BCP'D*. In C the area has remained constant during warping resulting in elongation of the margins, shortening along the axis, and no change along the neutral lines *E–N* and *F–M*.

which has been deformed by warping and then flattened out for comparison with the original area.

Cross-bending stresses resulting from torsional warping.—We have so far considered only the stresses resulting from change in area, and now turn to a consideration of the stresses due to warping or cross-bending. In Figure 9 a warped surface is represented in isometric projection. In one set of diagonals the lines curve downward toward their centers forming a synclinal depression. In the other set of diagonals the lines curve upward toward their centers and form an anticlinal elevation.

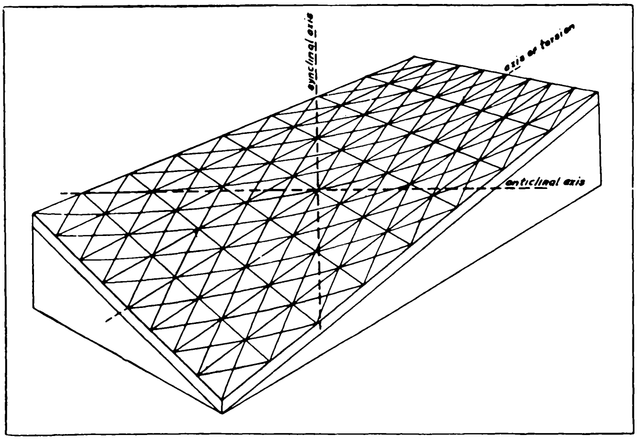

FIG. 9.—An isometric representation of a warped surface

If we consider a sheet of finite thickness to be thus deformed it is evident that on the upper surface compressional stresses will be developed at right angles to the axis of the synclinal depression and that tensional stresses will be developed at right angles to the axis of arching. At every point on the upper surface of this warped sheet there is a tensional stress and a compressional stress acting at right angles, each of them at an angle of 45° to the axis of torsion. On the lower surface it is evident that similar stress conditions exist but the tensional and compressional stresses are acting at angles of 90° to the similar stresses at the upper surface. These stresses are caused by cross-bending, and tensional conditions on one side mean compressional conditions on the opposite

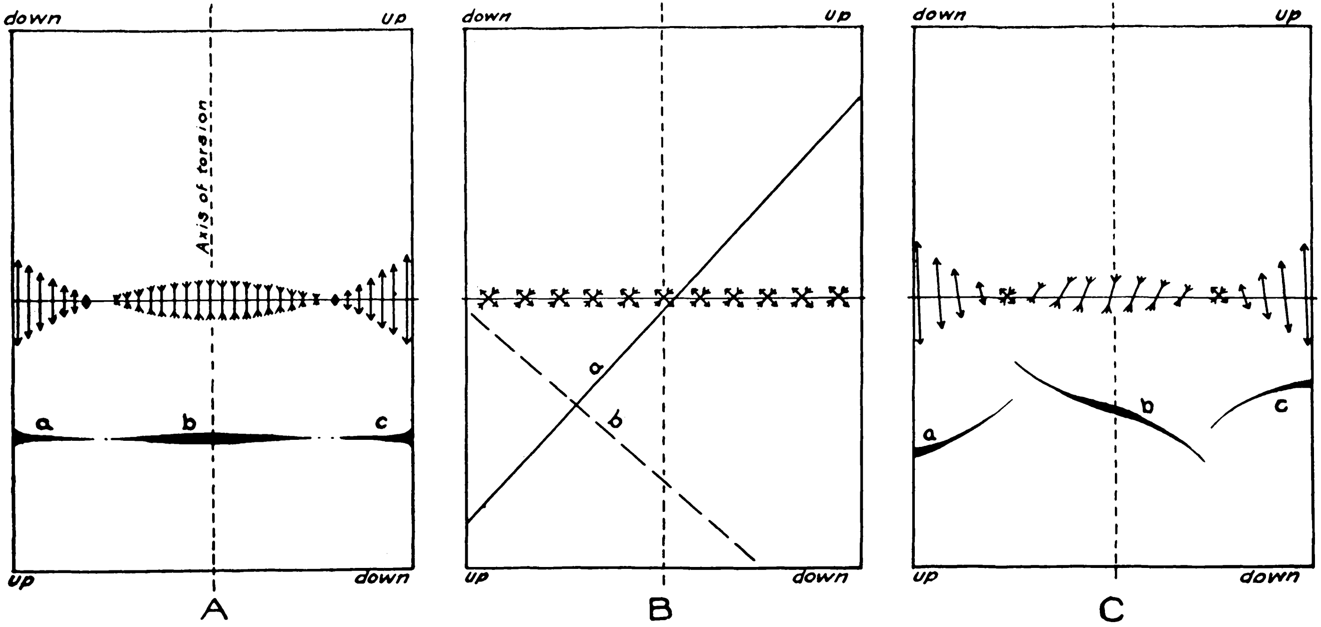

FIG. 10.—A. Stresses caused by local changes in area due to torsional warping, while the total area has remained constant. (See Fig. 8C.) Arrows indicate direction and relative magnitude of stresses *along any transverse line.* The heavy shaded lines indicate the direction and relative magnitude of resulting tension cracks at *a* and *c* and of compression fractures at *b.*

B. Stresses developed on the *upper surface* of a layer, due to bending caused by torsional warping. Arrows indicate direction and relative magnitude of stresses *along any transverse line.* The direction of tension cracks on the *upper surface* is indicated by the line *a.* The direction of tension cracks developed on the *lower surface* is indicated by the line *b.*

C. Resultants of stresses shown in A and B. Arrows indicate direction and relative magnitudes of resultant forces *along any transverse line.* The resulting type of tension cracks is shown by the shaded lines *a* and *c.* The shaded line *b* indicates the position and magnitude of the compression phenomena.

side just as in the case of a simple beam under load, in which compression is developed on the concave side and tension on the convex side.

Resolution of stresses due to change in area and to cross-bending—The stress condition at any point is the resultant of all of the stresses acting at that point. To determine conditions at a given point on the surface of a warped sheet it is necessary, therefore, to resolve the stresses due to cross-bending and the stresses due to areal change. In Figure 10A the stresses due to change of area caused by torsional warping are indicated in direction and relative magnitude by arrows. These represent the stresses occurring along *any transverse line of the warped sheet.* In Figure 10B the stresses due to cross-bending occurring along *any transverse line* of the warped sheet are shown by arrows in a similar fashion. In Figure 10C the resultants of the stresses in Figures 10A and 10B are shown. In Figure 10C typical cracks developed by tension and compression are shown at *a*, *b*, and *c*. The tension cracks *a* and *c* should begin at nearly 90° with the edge at the margin, and gradually curve to an angle of 45° at the neutral line. The curved line *b* indicates the strike of inclined thrust fractures which would be developed by compression. It is of interest to compare these curves with the tension cracks developed in paraffin on a rubber

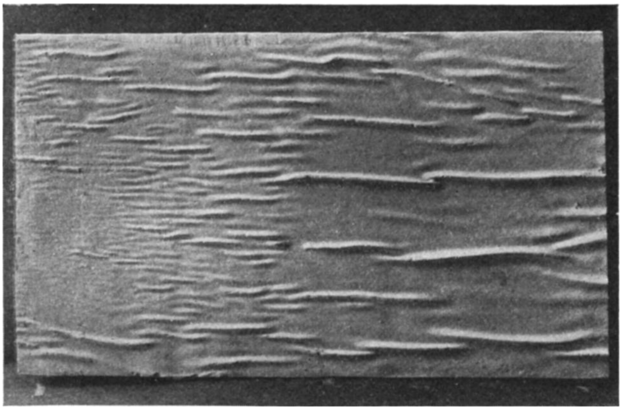

FIG. 11.—Plaster of Paris positive of folds produced by compression or shortening

sheet, illustrated in Figures 6 and 7. In this experiment constant distance between the clamps was maintained and compression along the center line thus prevented. The tension cracks are evidently due to a combination of cross-bending and stretching and are in accord with the conclusions indicated in Figure 10C.

Depending on the relative intensity of the stresses due to change in area and those due to cross-bending, the curvature of the cracks would vary· from the position in Figure 10A, due only to change in area, to the position shown in Figure 10B, due only to cross-bending.

Relative intensity of stresses due to cross-bending and those due to change in area.—With a given length of torsional axis the amount of cross-bending is a function of the angular displacement by torsion and is independent of the width of the warped sheet. The change in area (and therefore the tensional and compressional stresses), however, is a function of the width of the sheet as well as of the angle of torsion. It follows, therefore, that in narrow strips deformed by torsion, cross-bending stresses may be dominant while in wide areas a small angle of torsion with a small amount of resultant cross-bending may develop relatively large tensional and compressional stresses. Cross-bending stresses also increase with the thickness of the individual beds.

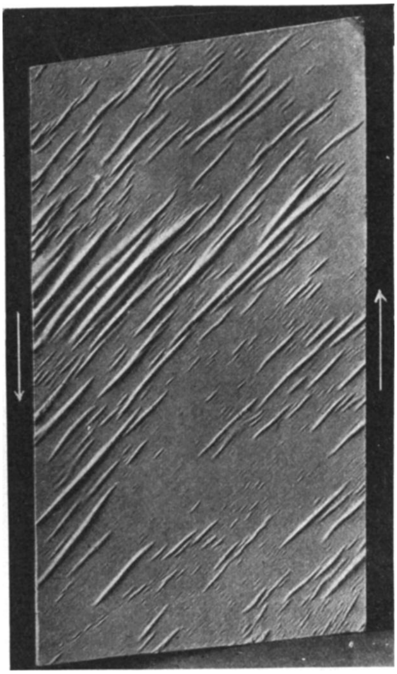

FIG. 12.—Vertical view of reproduction in plaster of Paris of folds produced by shearing deformation. The direction of movement is indicated by arrows and the amount of deformation is shown by the shape of the block.

The classical experiment of Daubrée,[1] in which he twisted a narrow strip of glass and obtained systematic sets of fractures at approximately 45° with the axis of torsion, is familiar to most students of structural geology. The fractures thus developed in the glass are evidently due to cross-bending. The writer has repeated the Daubrée experiment and found that one set of fractures in the glass developed as tension-cross-bending cracks on one surface and that the other set of fractures at right angles to the first developed as tension-cross-bending fractures on the opposite surface. Therefore, a brittle rock formation broken in the manner illustrated by the Daubrée experiment would show a conspicuous set of tension cracks at 45° to the axis of warping and the other set would not be apparent, as it would be developed from the underside of the deformed rock stratum. In other words, if we look for a repetition of the Daubrée experiment in the field we should look for only one set of parallel tension cracks.

Use of the apparatus in the study of folds.—Previous experimentation in the reproduction of the structures of folded rocks in the laboratory has, so far as the writer is aware, been by means of the type of apparatus employed by Willis.[2] This type of apparatus with various modifications has been used by Hall, Lohest, Favre, Daubrée, Cadell, and others. In his investigation of the mechanics of Appalachian structure Willis used an apparatus of the piston or plunger type in which a series of wax layers of varying consistency were built up to resemble in their relative competence the rocks occurring in the Appalachian region. A load of shot was superposed to simulate the weight of overlying sediments and deformation was accomplished by forcing a piston or plunger against the end of the aggregate by means of a screw. Willis found that with flat-laying layers single folds were developed near the plunger and that repeated folds could be developed only when certain portions of the beds had an initial dip or when the first fold next to the plunger piled up material to such thickness and strength as to develop, as it were, an extension of the plunger which in turn caused a secondary fold in front of it.

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[1] G. A. Daubrée, *Études Synthetiques de Géologie Expérimentale*, pp. 507–15.

[2] Bailey Willis, "Mechanics of Appalachian Structure, *Thirteenth Ann. Rept. U.S. Geol. Survey*, Part 2 (1893), pp. 241–53.

The apparatus of Willis permits deformation only by straight shortening or compression and does not afford means of studying the nature of folds developed by lateral shearing movements. It seems probable that the movements between great earth masses are in the nature of shears rather than simple straight-line compression. In other words, *the application of a compressive force directly toward the point of maximum resistance would be less probable than the development of a couple which would cause what has been called a rotational stress.*

It does not appear to the writer that rocks have been folded by forces transmitted to them in a manner at all similar to the action of a piston against a more or less confined mass but that shortening of the earth's crust has resulted from great compressive forces extending to some depth, and that the fracture and folded rocks within the zone of our observation have received from the rocks beneath, in a large measure, the force which deformed them. In other words, most of the faults or folds are the result of the riding or dragging of the upper layers by the underlying materials.

The writer has attempted to apply to the study of folds the methods used in the study of fractures already described. The two pieces of apparatus shown in Figures 1 and 4 were employed but instead of the thin brittle coat of paraffin a very thin layer of plastic wax (made by mixing beeswax and Venice turpentine) was applied and over this, while the wax was still sticky, a sheet of tinfoil was carefully spread. When the rubber sheet was allowed to shorten, or was deformed by shear, the layer of wax and tinfoil developed a series of folds. It was found that a very thin sheet of rubber served the same purpose as the tinfoil. The purpose of the thin sheet of rubber or tinfoil is to supply a layer with a certain small amount of competency. A layer of wax alone is entirely incompetent and follows the deformation of the rubber sheet without development of folds. A thin layer of tinfoil, sheet rubber, or waxed paper supplies the element of competency which results in the development of folds.

Folds developed by pure shortening or compression.—The apparatus shown in Figure 2 was employed, with a layer of plastic wax covered by a sheet of thin dental rubber. The shortening was produced by allowing the thick rubber sheet to contract. This resulted in the development of the system of folds illustrated in Figure 11. This figure represents a positive reproduction of the surface of the specimen in plaster of Paris. The original specimen was not of a nature to be easily photographed. This experiment and others of the same type show a set of folds striking in a direction at right angles to the direction of shortening. All of these folds pitch at the ends and disappear. Depending on the thickness of the wax and the behavior of the rubber sheet, shortening is accomplished by a few large folds or by a larger number of smaller folds. An interesting overlapping of the folds is noted. Whenever a fold terminates by pitching, another fold appears overlapping it and continuing the necessary amount of shortening. The experiments demonstrate very well that pitching folds do not necessarily mean cross-folding but that they are developed in flat-lying beds with perfectly even application of shortening stresses.

Development of folds under conditions of shear or rotational stress.—The apparatus used is illustrated in Figure 4, except that in place of a thin layer of paraffin, a very thin layer of plastic wax was applied to the very tightly stretched rubber sheet and over this a sheet of tinfoil was carefully spread, care being taken to secure perfect adhesion of the tinfoil to the underlying wax. Deformation was accomplished by causing the slidable clamp to move parallel to the other clamp by means of the screw. This resulted in a set of folds in the tinfoil-covered wax layer, shown in Figure 12. The illustration is from a photograph of a positive reproduction of the specimen in plaster of Paris. The direction of shearing forces is shown by the arrows and the amount of deformation by the shape of the parallelogram which was originally rectangular. The folds, it will be noted, have their axes parallel to the direction of elongation of the mass. All of them are pitching folds. They illustrate the phenomenon of repeated folds. Like the previously described experiment they demonstrate that pitching folds do not necessarily mean cross-folding or shortening in the direction of the axes. As a matter of fact, in this experiment tensional stresses existed in the direction of the axes of the folds and actual open ruptures in the tinfoil occurred across some of the folds but were not preserved in the process of casting.

A rather striking similarity between the folds illustrated in Figure 9 and the structure of the southern Appalachians is apparent and the writer ventures to suggest that perhaps certain of the characteristics of the southern Appalachian structure, such as repeated folds, pitching folds, and repeated thrust faults, may receive a certain amount of new light by viewing them with the conditions of the above-described experiment in mind. Whether the deformation was accomplished by straight compression between the oceanic segment and the continental mass or by a shearing movement between these great segments cannot be said. It seems, however, that the latter is rather more probable mechanically and that the foregoing experiment demonstrates that the folds of the Appalachians could have been produced by such shearing movement.